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Thixotropy of soft clay: A review

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ABSTRACT

Thixotropy of soil is, after softening by remoulding, a process of time-dependent return to a harder state under constant water content and constant volume conditions. This paper presents a critical review of previous investigations on the thixotropy of soft clay. Thixotropic behavior is primarily a structural effect accompanied by the spontaneous dissipation of excess internal energy, and some microstructural observations provide a deeper insight into its mechanism. Mathematical theories and models to simulate thixotropic strength recovery of soil are introduced. Different test methods to evaluate the thixotropic behavior of soil are summarized. Correlations between the thixotropic behavior of soil and some basic indexes, such as water content, Atterberg limits, mineralogy, activity and salt concentration, are described. Some remarks on future improvement for thixotropy of soil are also provided based on the results of up-to-date research.

1. Introduction

The term "thixotropy" was originally proposed by Peterfi (1927) and used by Freundlich (1935) to describe a phenomenon of reversible changes of colloidal solutions from fluid conditions to an elastic solid-like gel. The definition of thixotropy has been widely used in geology and soil mechanics. For example, it was defined as a process of softening caused by remoulding, followed by a time-dependent return to the original and harder state (Burgers and Blair, 1949). Mitchell (1961) described thixotropy as an isothermal, reversible, time-dependent process occurring under conditions of constant composition and volume, whereby a material stiffens while at rest and softens or liquefies upon remoulding. ASTM (D653-14), 2014 defined thixotropy as "the property of a material that enables it to stiffen in a relatively short time on standing, but upon agitation or manipulation to change to a very soft consistency or to a fluid of high viscosity, the process being completely reversible".

The thixotropic phenomenon of materials with time can be illustrated in Fig. 1 (Skempton and Northey, 1952). In an undisturbed state, the initial shear strength is $S_{u,0}$. Due to remoulding, the strength will decrease to $S_{u,r}$. Under conditions of constant water content and volume, the strength after a period, t, will increase to $S_{u,t}$, where $S_{u,t} > S_{u,r}$. For an ideal purely thixotropic material, if given enough time, the strength will revert to its initial value, $S_{u,0}$. Remoulding the material will reduce the strength again to the value $S_{u,r}$ (Fig. 1a). While for the partially thixotropic material, its strength will hardly recover to the initial state (Fig. 1b). Thixotropy strength ratio, A_t ($=S_{u,t}/S_{u,r}$), is usually used to evaluate the thixotropic potential of soil. Previous researches show that most natural soils belongs to partially thixotropic material.

Thixotropic phenomenon of soil has long been investigated in the field of geological and geotechnical engineering. Boswell (1948) summarized that, except coarse clean sands and gravel, all sediments are proved to behave thixotropy. The degree of thixotropy depends on grain-size, grading, mineralogical composition and the presence of electrolytes. The effect of thixotropy of soil on some engineering geological hazards, for example landslides and lahar, has long been focused by many researchers (Solonenko, 1977; Khaldoun et al., 2009; Cronin et al., 1999; Mainsant et al., 2015; Yenes et al., 2020). Kerr and Drew (1968) studied quick-clay slides and found that, after resting about 40 min, the earthquake-remoulded clay regains to its water-saturated strength. While Cabrera and Smalley (1973) concluded that quick clays are not thixotropic, or its thixotropy is only very slight. Frydman et al. (2007) presented a preliminary study regarding change in residual strength with elapsed time in landslides with marly profiles. Hu et al. (2017) conducted ring shear test on mudstone granules of different size obtained from a landslide shear zone, and they found that thixotropic

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and shear-thinning behavior of the mud may play a role in some landslide kinematics. From an engineering point of view, the thixotropic property of soil could have a positive significance. For example, soon after installation of piles or suction anchors, the shear strength recovery of remoulded clay along the wall could provide essential friction (Andersen and Jostad, 2002). Kul'chitskii (1975) found that the strength of soil surrounding piles increases up to 0.85 times the bearing capacity after one month. It is unclear, however, whether this strength increase is only due to thixotropy, or if it could also be due to redistribution of pore pressure in the remoulded zone near the pile. Romanov and Romanov (1997) provided a complex procedure for the impression of reinforced-concrete piles through leader holes under complex geologic-engineering conditions with supplementary use of soil thixotropy. Andersen and Jostad (2002 and 2004) summarized data from in-house tests and from literature and recommended lower and upper limits of the thixotropy factor for design of suction anchors. Huang and Wang (2016) added a nanomaterial, laponite, to silty sand, and found the soil's liquefaction resistance significantly increases because of the strong thixotropic property of the gel. Yoon and El Mohtar (2014) tried to use the thixotropic behavior of sodium pyrophosphate modified bentonite suspensions to control seepage problem. Furthermore, some standard (for example, Det Norske Veritas, 2005) already has strongly recommended considering the thixotropic effect on the geotechnical design and installation of suction anchors in clay.

The purpose of the present paper is to provide an overview of the studies on the thixotropy of soil. Firstly, the thixotropic mechanism of soil is highlighted and microstructural changes during thixotropy are presented. This is followed by an introduction of mathematical theories and models used to predict or simulate thixotropic strength recovery of soil. Then different test methods to evaluate the thixotropic behavior of soil are summarized and compared. Subsequently, relationships between the thixotropic behavior and geotechnical properties, such as water content, Atterberg limits, mineralogy, activity and salt concentration, are described. Finally discussions on possible future studies of soil thixotropy for engineering application are given.

2. Thixotropy mechanism and model

2.1. Thixotropy hypothesis and microstructural changes

Day (1954) thought that the internal energy and stress conditions in a soil are not equal immediately after remoulding. Based on this assumption, Mitchell (1961) proposed a systematic hypothesis as one possible mechanism to explain thixotropic behavior of soil. It is primarily regarded as a structural effect, including particle arrangement, change of adsorbed water structure and distribution of ions in the ambient fluid phase. And the occurrence of this process is accompanied by the spontaneous dissipation of energy. Díaz-Rodríguez and Santamarina (1999) also believed that local thermal, chemical, mechanical or electrical transport in soil could take place at the microscale during thixotropy.

The thixotropic processes may be visually illustrated as in Fig. 2. When a soil is remoulded or compacted by applied shearing stresses, the arrangement of platy clay particles is changed to a uniform and parallel pattern, as shown in Fig. 2a. The externally applied energy is spent in breaking the particle bonds to form a weak and dispersed system, with the repulsive forces stronger than the attractive forces between particles. As particle bonds are broken, there is a slight rising in temperature (Blake and Gilman, 1970; Rinaldi and Clariá Jr, 2016). The energy of interaction between particles is at a high level commensurate with the externally applied forces. Furthermore, the adsorbed water layers and ions distribution are also in accordance with this high energy level.

After the externally applied energy barrier is removed, the attractive forces subsequently are over the repulsive forces (Fig. 2b). Consequently, the soil-water-electrolyte system attempts to adjust itself to a new and lower energy level. Then a spontaneous dissipation of the excess internal energy occurs, and the minimum energy condition demands that particles flocculating. At the same time, local ions in the double layer will redistribute and a slightly altered adsorbed water structure will form. As a result, there will be some significant changes in the physical behavior of the soil. After given enough time, as shown in Fig. 2c, the final equilibrium of the system is achieved, with attraction forces equal to repulsion forces between particles. In summary, the mechanism of soil thixotropy is mainly a process of microstructure recovery accompanied with increase in flocculation which is formed through reorientation and rearrangement of particles, change of adsorbed water structure and redistribution of ions.

Based on microstructural observations, some findings might provide evidence for the above hypothesis. Zhang et al. (2017) studied the thixotropic behavior of Zhanjiang clay in southern China by the methods of scanning electron microscopy and mercury intrusion porosimetry. As shown in Fig. 3a, intact soil exhibits an open flocculated structure with particles and domains interconnected mainly through edge-to-face and edge-to-edge patterns. When the soil is disturbed (Fig. 3b), the damage to the bonds between particles forces the structural features to evolve from flocculated to dispersed, with face-to-face pattern dominated (corresponding to Fig. 2a). As time increases (Fig. 3c to e), the soil structure gradually changes from dispersed to flocculated due to the unbalance in the attractive and repulsive forces between particles (corresponding to Fig. 2b). Furthermore, the local ions and adsorbed water layers are believed to move and change. With prolonged thixotropy time (Fig. 3f to h), the soil will gradually exhibit an open flocculated structure once again (corresponding to Fig. 2c). Another notable finding is that the pore size distribution tends to homogenization during thixotropy time.

Osipov et al. (1984) observed the microstructural changes of thixotropic soil during deformation in a rotary viscometer with and without vibration, as shown in Fig. 4. Under static shear condition (0–A),

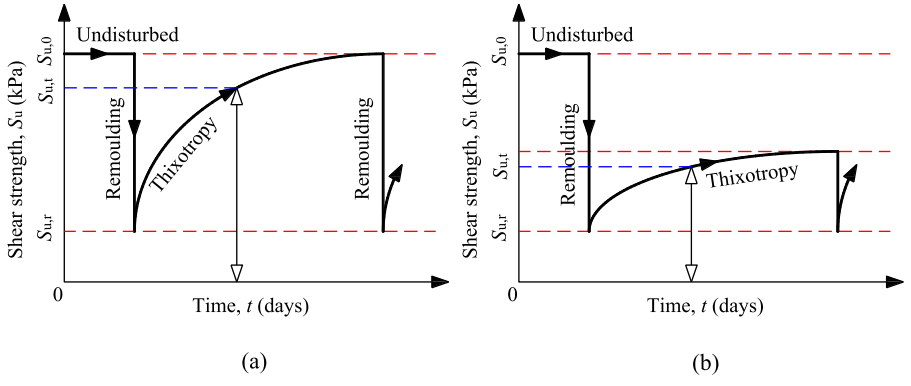

Fig. 1. Schematic diagram of thixotropic process (redrawn from Skempton and Northey, 1952): (a) fully thixotropic material; (b) partially thixotropic material.

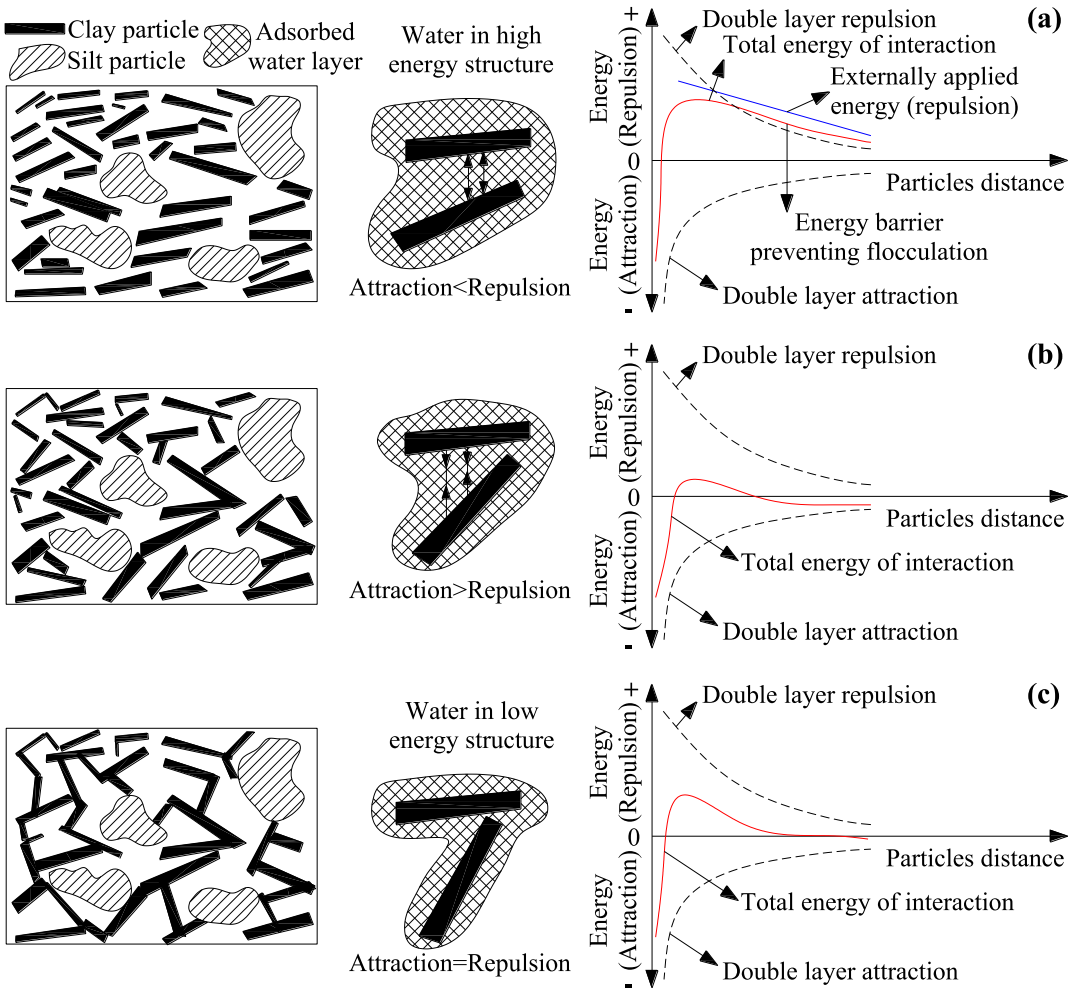

Fig. 2. Schematic diagram of thixotropic structure change and energy-distance curves between clay particles (redrawn from Mitchell, 1961): (a) during remoulding, (b) at rest, thixotropy hardening partially complete, and (c) at the end of thixotropic hardening.

reversible elastic deformations dominates because of the partial tilting of particles and microaggregates in the direction of the shear force. Removing load at this stage would lead to elastic restoration with time because of thixotropy. At stage A-B, the elastic deformation gradually changes to viscoplastic in the local shear zone, followed by the development of negative pore pressure, an increase in soil porosity and water content. Under dynamic shear, the impact of vibration leads to a drastic reduction in the shear resistance (B–C). Up until the cessation of impact (C–D), the shear resistance remains constant, with a more homogeneous microstructure appearing along the entire gap of the viscometer. When cessation of vibration (D–E), the soil structure rapidly restores due to thixotropy, with increasing in micro-aggregate size and formation of larger pores. Therefore, the final soil microstructure forms less homogeneous porosity and the soil microstructure recreated is similar to the initial one. However, the results obtained by Zhang et al. (2017) shows that the pore size distribution tends to be homogenization because of the particle movement resulting from the unbalance between attractive and repulsive forces. To the authors' knowledge, the differences between them might be related to the various soil samples with quite different water content. After thixotropic hardening partially completes and static shears the soil once again, the resistance with time (E–F) will be like stage A–B. Jacobsson and Pusch (1972) focused on the thixotropic recovering of quick clay by means of transmission electron microscopy (TEM) with ultra-microtome sectioning and nuclear spin echo technique. The results show that such strength regain is due to particle reorientation, but emphasizing the action of smaller particles, as well as improvement of the ordering of water molecules.

As for the methods to investigate the microstructural changes during thixotropy, the scanning electron microscopy and mercury intrusion porosimetry are two general used tools. However, the specimens used for these microcosmic observations or measurements need to be cut into small pieces and dried. As a result, the microstructural investigation cannot be focused on nor the same sample neither the same position, especially for thixotropy test. Therefore, some more advanced methods, such as environmental scanning electron microscopy (ESEM) (Sun et al., 2019; Pardo et al., 2019) and computed tomography (CT) (Gagnoud et al., 2008; Sun et al., 2020), are recommended as the prior choice for thixotropy microstructural test, since the same sample and non-destruction process could be well guaranteed. Nonetheless, up to now, the knowledge about the mechanism of soil thixotropy is still qualitative and sometimes speculative. In contrast, significant understanding of thixotropy in colloid systems or gels has been well achieved using the latest analytical techniques (e.g., light, neutron, and X-ray scattering). Lately, Aminpour (2019) made a try to develop a versatile molecular dynamics simulation tool to accurately duplicate the time-dependent interactions between clay particles, and it could help to deeply understand the micro- to macro-linkage of soft clay thixotropy. Therefore, in the authors' opinion, the geological and geotechnical study on the mechanism of soil thixotropy might need further investigations through referring to the researches performed by colloid scientists.

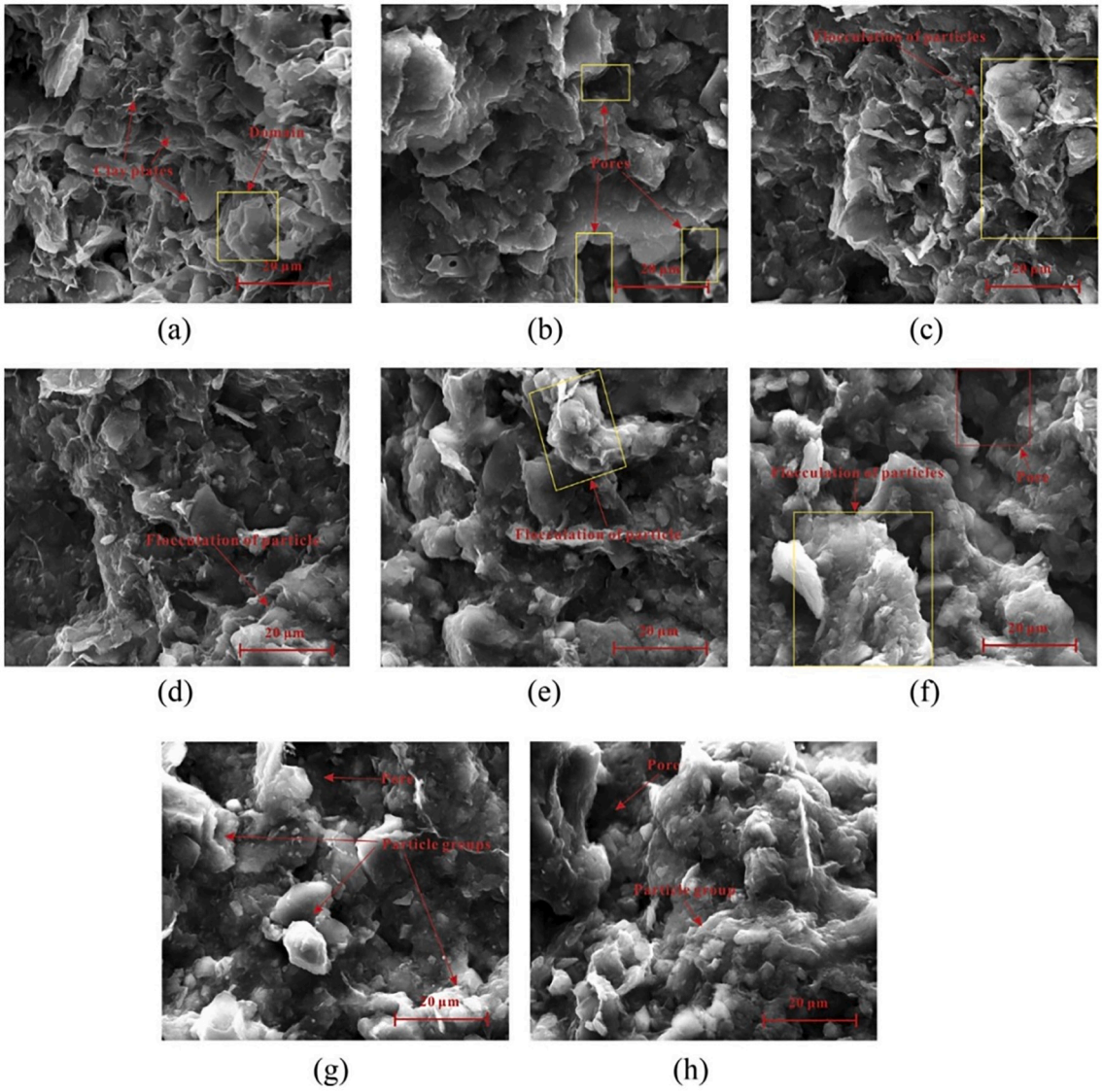

Fig. 3. Micro-images of (a) intact soil and remoulded soil at different thixotropic times, (b) 1 d, (c) 3 d, (d) 7 d, (e) 30 d, (f) 100 d, (g) 300 d, and (h) 500 d (Zhang et al., 2017).

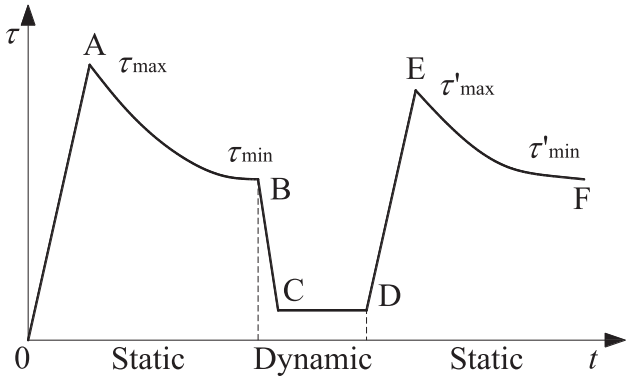

Fig. 4. Shear resistance (τ) with time (t) relationship for soil subjected to static and dynamic shear conditions (redrawn after Osipov et al., 1984): 0–A shear resistance of the undisturbed structure under static conditions; A-B shear resistance for the ruptured structure; B–C drastic drop in strength after vibration; C–D shear resistance of the ruptured structure with vibration; D–E strength restoration after cessation of vibration; and E–F shear resistance of the thixotropy restored structure with static shear after cessation of vibration.

2.2. Mathematical models

Dexter et al. (1988) proposed a simplified theory to describe the thixotropic behavior of soil by focusing on particle rearrangement. The failure strength of soil, $S_{u,0}$, is given by

$$S_{u,0} = N(P)\frac{b}{A} \tag{1}$$

where $N(P)$ is the number of particle-particle bonds during thixotropy, influenced by the applied levels of effective stress, P, A is the area of failure surface generated, and b is the average force required to break the bonds.

The strength of soil at time, t, is given by

$$S_{u,t} = [N(P) + n(t)]\frac{b}{A} \tag{2}$$

where $n(t)$ is new formed bonds due to thixotropy, assuming the $n(t) = 0$ at $t = 0$ and that $n(t)$ is independent of $N(P)$. The increase in strength and its rate with time are shown in eqs. (3) and (4), respectively, and they are independent of the value of compaction.

$$\Delta S_u = n(t)\frac{b}{A} \tag{3}$$

$$\frac{\partial S_u}{\partial t} = \frac{b\partial n(t)}{A\partial t} \tag{4}$$

The thixotropic strength ratio is given by

$$A_t = \frac{S_{u,t}}{S_{u,0}} = 1 + \frac{n(t)}{N(P)} \tag{5}$$

A_t depends on P, for example, with higher values of P, $N(P)$ will be larger, and A_t will be smaller at any time t. It means that the amount of the thixotropic strength recovery is strongly related to the magnitude of effective stress (Mitchell, 1961). At higher effective stress, the rearrangement of particles is less easy, because the particles are strongly restricted (Doglioni and Simeone, 2013).

Another relation to capture the thixotropic behavior changes was proposed by Heymann et al. (1996), and it is called stretched exponential thixotropy model:

$$\sigma_y(t) = \sigma_y^0 + \left[\sigma_y^\infty - \sigma_y^0\right]\left(1 - e^{-(t/\lambda)}\right) \tag{6}$$

where σ_y^0 and σ_y^∞ represent the yield strength immediately after remoulding and after a long time, respectively. λ is defined as a constant related to the property of material. Zhang et al. (2013) found that the Weibull modulus is good quantitative descriptor of the thixotropic evolution of clay floc microstructure, and it can be well fitted using the stretched exponential thixotropy model mentioned above. Afterwards, Abu-Farsakh et al. (2015) introduced a time-dependent reduction parameter, β, to eq. (6). They utilized the relation in the finite element model to simulate the thixotropic effect on the strength increase of surrounding soil after pile installation. The results show good agreement with values obtained from full-scale instrumented pile load tests. However, in the authors' opinion, whether or not the strength recovery is due to pure thixotropic effect is not very clear. Recently, Aminpour (2019) developed a multiscale bottom-up framework for modeling clay properties in order to understand the physics governing macroscale thixotropic behavior. Furthermore, some rheological theories, such as viscous, viscoelastic or viscoplastic models (Barnes, 1997; Dullaert and Mewis, 2006; de Souza Mendes, 2009) for suspensions or gels, can be referred to describe thixotropic behavior of soil.

Thixotropy is a very important factor to influence the strength changes of soil during landslides or after installation of foundations. So how to build a satisfied model of thixotropy or regard it as a supplementary factor to add in some current models by considering time-dependent effect is essential in the future research.

3. Test methods

During thixotropy, changes in the physical behavior of soil, such as undrained shear strength, viscosity, yield stress, stiffness or shear modulus and water matric suction, are measured by varied test methods summarized in Table 1. Fall cone test becomes a more and more popular method to estimate the strength changes of soft clay. Vane shear test is also a frequently used method to investigate the thixotropic strength recovery of soil. However, it is found that vane shear test provides lower values than fall cone test, and the reason could be that sample is largely disturbed by the insertion of the vane before shearing (Park et al., 2014; Shahriar et al., 2018).

In addition, some other laboratory test methods for measuring soil strength changes are also utilized, such as unconfined compression test, motor driven or manumotive cone penetration test, direct shear test, ring shear test and cyclic full-flow penetrometer test. However, the same testing conditions could not be guaranteed by using conventional destructive test methods as those mentioned above (Seng and Tanaka, 2012; Rinaldi and Clariá Jr, 2016). The weak structure formed by thixotropy could be strongly destroyed during sample preparation. Then the obtained results might become less reliable or even incorrect. Bender element test is recommended to measure the change of shear modulus of soil to reflect thixotropic hardening, since it is a nondestructive method (Seng and Tanaka, 2012).

Table 1
Summary of thixotropy test methods.

Thixotropic behavior	Test method (apparatus)	Researchers
Undrained shear strength	Fall cone test	Lu et al., 1991; Díaz-Rodríguez and Santamarina, 1999; Jeong et al., 2012; Park et al., 2014; Chan and Yong, 2014; Yang and Andersen, 2016; Shahriar et al., 2018; Doughty et al., 2018
	Vane shear test	Suthaker and Scott, 1997; Jeanjean, 2006; Seng and Tanaka, 2012; Zakeri et al., 2014; Chan and Yong, 2014; Chan, 2015; Park et al., 2014; Shahriar et al., 2018
	Unconfined compression test	Moretto, 1948; Yalcin and McIntosh, 1961; Díaz-Rodríguez and Santamarina, 1999; Zhang et al., 2017
	Cone penetration test	Jacobsson and Pusch, 1972; Utomo and Dexter, 1981; Dexter et al., 1988; Zhang et al., 2017
	Direct shear test	Rinaldi and Clariá Jr, 2016; Kamil and Aljorany, 2019
	Ring shear test	Doglioni and Simeone, 2013; Hu et al., 2017
	Full-flow penetration test	Al-Janabi and Aubeny, 2019
Yield stress or viscosity	Rheometer or viscometer	Boswell, 1948; Kerr and Drew, 1968; Osipov et al., 1984; Perret et al., 1996; Suthaker and Scott, 1997; Yap et al., 2011; Jeong et al., 2012; Abdou and Ahmed, 2013; Yoon and El Mohtar, 2014; Jeong et al., 2015; Stempkowska et al., 2017
Shear modulus	Bender element	Seng and Tanaka, 2012; Rinaldi and Clariá Jr, 2016
Water matric suction	Tensiometer	Rinaldi and Clariá Jr, 2016
Electrical resistance and capacitance	Impedance analyzer	Rinaldi and Clariá Jr, 2016

For soils with higher water content, such as drilling mud, bentonite suspension, clay paste or slurry, thixotropy is regarded as a special rheological phenomenon, and rheometer or viscometer is usually used to measure the changes of yield stress or viscosity. Especially, Osipov et al. (1984) modified a rotary viscometer by adding electrodynamic vibrostand and liquid nitrogen container for sample freezing to investigate the microstructural changes taking place in thixotropic soil. This apparatus can help to examine the microstructural behavior of soil at any stage of thixotropy, providing a better understanding of thixotropic phenomena. Recently, Rinaldi and Clariá Jr (2016) designed an integrated test device which is called adiabatic cell, and it can keep the samples at constant conditions during the thixotropy process. The cell allows monitoring and capturing the changes of shear modulus, temperature, electrical resistance and capacitance and water matric suction in the samples during remoulding and resting in real time.

According to the requirement of thixotropy test, keeping the constant water content and volume during storage time is essential, especially for samples with long-term preservation. The method introduced by Yang and Andersen (2016) using a double conical plastic container is relatively effective to reduce water loss with time. However, water content measurements indicated that some changes did occur, and the decrease of water content for many tests reached even more than 10% after remoulding. In addition, the design of appropriate container should meet the demand of strength test operation. In the authors' opinion, the design of container for thixotropy test should be paid more attention.

How to accurately measure the strength regain of samples at different time, especially to successfully capture the strength changes at the early thixotropy stage is very important. So the selection of test method or apparatus depends much on the shear strength of soil samples and its accuracy. At the same time, preparing and operating soil samples should be careful and avoided disturbance, since the recovered structure due to thixotropy effect is very vulnerable. If possible, fall cone and bender element are recommended to be the prior methods for thixotropy test.

4. Correlations between thixotropic behavior and geotechnical properties

4.1. Water content and Atterberg limits

Water content has been used as an important parameter to evaluate the thixotropic magnitude of soil, and its effect has been discussed by many researchers. Skempton and Northey (1952) pointed out that the thixotropy decreases with decreasing water content below the liquid limit, w_L, and it is thought that thixotropy might be negligible with water contents at or close to the plastic limit, w_P. However, many researchers (Moretto, 1948; Seed et al., 1961; Mitchell, 1961; Utomo and Dexter, 1981) found that thixotropic strength regain in compacted soil (unsaturated soil) could still occur at water contents even below w_P. Mitchell (1961) concluded that thixotropy has the greatest effect at water content between about 0.56 and 0.74 times w_L. Shahriar et al. (2018) also observed that the maximum strength recovery of samples is obtained at water content close to 0.75 times the w_L. Seng and Tanaka (2012) found that, regardless of soil types, the thixotropic effect on the shear modulus is significant at water content around w_L. While at lower or higher water contents the thixotropic hardening becomes less prominent. However, the results from Zhang et al. (2017) presents that Zhanjiang clay shows a higher thixotropic strength ratio, even though its water content is much lower than w_L.

Chan (2015) compared the strength recovery of two remoulded dredged marine clays and found that the smaller the initial water content, the less time is required to attain thixotropic hardening. According to a database including marine clays from 15 offshore sites, Andersen and Jostad (2002) found that the thixotropy strength ratio increases with increasing plasticity index, I_P, but the scatter is significant, as shown in Fig. 5. The thixotropy is higher when $I_P > 40\%$, compared with $I_P < 40\%$. Despite the scatter, the researchers proposed to use the lower limit of the thixotropy strength ratio band in Fig. 5 to calculate the strength increase with time, unless site-specific data is available. In some cases, for example the temporarily stopping of pile or suction anchor penetration, the upper limit of the thixotropy strength ratio should be considered and used to evaluate the penetration force, unless site-specific data is available. Yang and Andersen (2016) critically examined the data in Andersen and Jostad (2002), excluded data where there could be some change in water content with time and added some additional data. They studied correlations with different parameters and concluded that the higher the water content, plasticity index and liquidity index, I_L, the higher the thixotropy strength ratio will be. Again, it seems the increasing trend changed at about $I_P = 40\%$, as shown in Fig. 6. Their research work could significantly expand the scope of the application of these empirical correlations in practical engineering design.

The effect of water content on thixotropy of soil might generally be explained as follows (Mitchell, 1961; Dexter et al., 1988). For a given soil at a lower water content, the soil particles are strongly flocculated because of the lack of double layer water, so the rearrangement of particles are strongly restricted by the interactive forces. Therefore, thixotropic strength regain will be negligible. While at very high water content, the attractive forces between particles become extremely weak, so the soil particles disperse. As a result, thixotropy is also insignificant. At water content close to w_L, the motion and reorientation of particles become more inclined to flocculate, resulting in a larger strength increase.

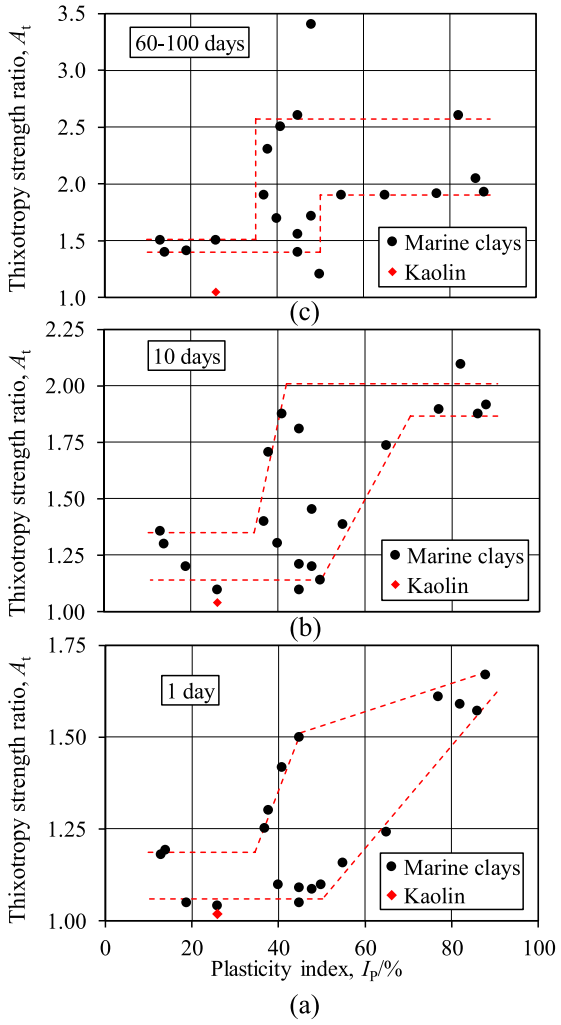

Fig. 5. Thixotropy strength ratio as function of plasticity index (redrawn from Andersen and Jostad, 2002).

4.2. Clay mineral and activity

The potential and magnitude of thixotropy is also much dependent on the mineral composition of soil. After testing and comparing different clay minerals, Skempton and Northey (1952) found that the thixotropic behavior of bentonite is most remarkable even after very short time. While the kaolin shows almost no thixotropy and illite shows only a small effect. Similar results were also obtained by Shahriar et al. (2018). Activity was defined by Skempton and Northey (1952) as the ratio between plasticity index and clay fraction, and it could reflect the dominant kind mineralogy of soil. Jeong et al. (2015) investigated and compared the thixotropic behavior of soils with high and low activity. It shows that the thixotropic effect on high active soil is more obvious than that of low active clay. Shahriar et al. (2018) found that thixotropic strength ratio increases with an increase of activity in two aging periods (1 day and 8 days) at a water content of 0.75 w_L for six kinds of clay. Abdou and Ahmed (2013) also concluded that the more bentonite particles in the suspensions, the stronger the thixotropy will be. Andersen et al. (2008) plotted the data from Lunne and Andersen (2007) as function of thixotropy strength ratio and activity, as shown in Fig. 7. It presented that there is some relationship between the thixotropy strength ratio and activity, but the discreteness of data is considerable. However, when sorting the data according to the sensitivity (with 4.5),

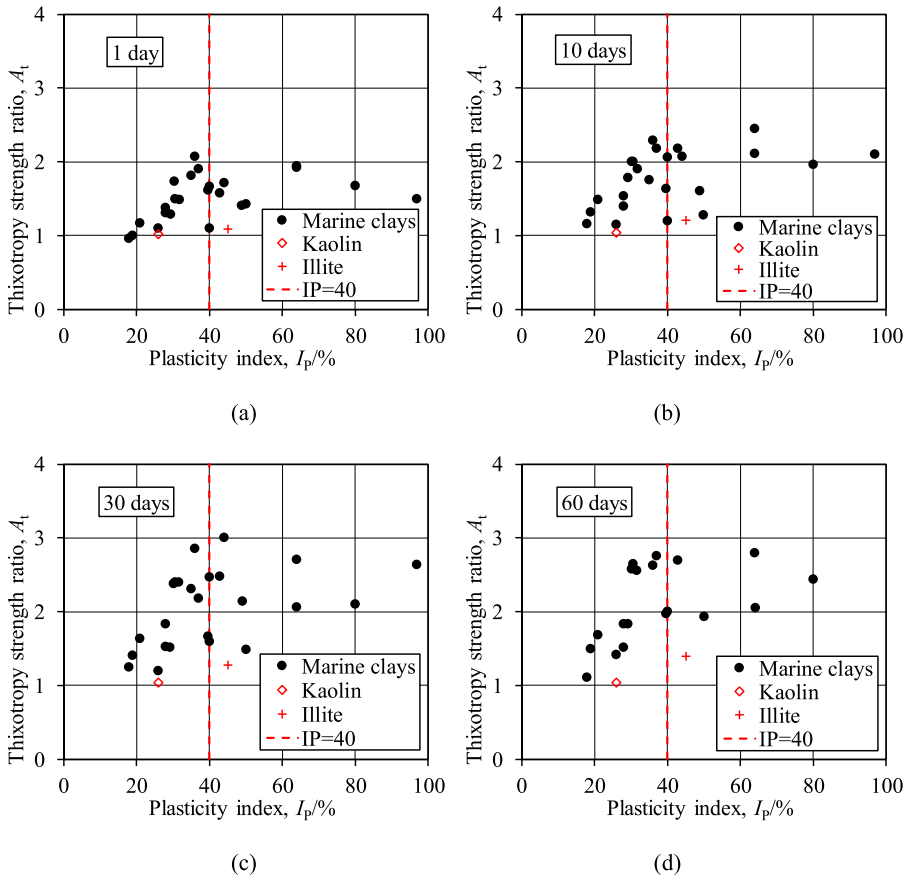

Fig. 6. Thixotropy strength ratio versus plasticity index (redrawn from Yang and Andersen, 2016, kaolin and illite from Skempton and Northey, 1952).

the effect of sensitivity on the scatter is reduced. In addition, the estimated average trend lines change when the activity is equal to 1.0. The data for kaolin, illite and bentonite form a lower bound to the data for the natural clays. While considering using these data for design, a low value within the thixotropy strength factor scatter for the given activity should be chosen when a low strength is conservative, for example capacity analyses. If a high strength is conservative, like in removal of suction anchors, a high value should be selected.

These findings provide evidence that the presence of active clay minerals could increase the thixotropic strength ratio. This is attributed to the different crystal structure of different clay minerals. For example, kaolin is formed by 1:1 layer structure, while bentonite is with 2:1 layer structure. Compared with the low active mineral, the high active mineral has a larger specific surface, which could provide a higher cation exchange capacity and larger quantities of electric charge (Zhang et al., 2017). All these factors could improve the happening of thixotropy.

4.3. Salt concentration

Salt concentration also has a large influence on the thixotropic characteristic of a soil. Jeong et al. (2012) found that, with increasing salinity, the montmorillonite-rich clays show significant changes in the thixotropic behavior, such as apparent yield stress and plastic viscosity. Lu et al. (1991) found that the thixotropic strength ratio of a sample prepared with fresh water is slightly higher than that of sample with salt water. Perret et al. (1996) investigated a clayey mud with salinities ranging from 0.1 to 30 g/l. The results indicate that slurries with lower salinity show higher thixotropic effect than those with higher salinity. Abdou and Ahmed (2013) studied a kind of bentonite suspensions with three different salt concentrations. The results show that the suspension with no salt and lower salt concentration exhibites thixotropy, while there is almost no thixotropy for suspensions with higher one. Rinaldi and Clariá Jr (2016) prepared sodium bentonite slurries at different NaCl concentrations to investigate its effect on the water tension and shear wave velocity during thixotropy. They found that the rate of increase in water tension is higher for the sample without salt than that of the sample with salt concentration of 10 g/l. In addition, the time required to stabilize the unsalted sample is much longer than the sample with NaCl. However, there is no correlation of the shear wave velocity with respect to salt concentration.

The possible reason is that the concentration of salt in the pore water could largely change the thickness of the electrical double layer between clay particles. At low salt concentration, an open structure forms in an edge-to-face fabric due to the opposite charges of the edges and of the faces of particles (Olphen, 1977). At this state, the interparticle bonds would be strong enough to induce a quick rearrangement of particles to form flocculation (Perret et al., 1996), so thixotropy will be significant. While at high salt concentration, electrical double layers around the clay platelets shrink and particles become closer to form greater aggregate sizes, with an edge-to-face and face-to-face fabric due to long range Van der Waals attraction forces (Olphen, 1977). In this case, particle rearrangement becomes weak or even impossible, and as a result it will exhibit less thixotropic effect.

The effect of salt concentration discussed above is valid for the effect of salt concentration during deposition or formation of the clay. The effect can be different when the salt concentration is reduced due to water flow through a deposit after it has been deposited in a saline environment. This can be the case for sensitive clays, as mentioned by Andersen et al. (2008) and referenced in the previous section.

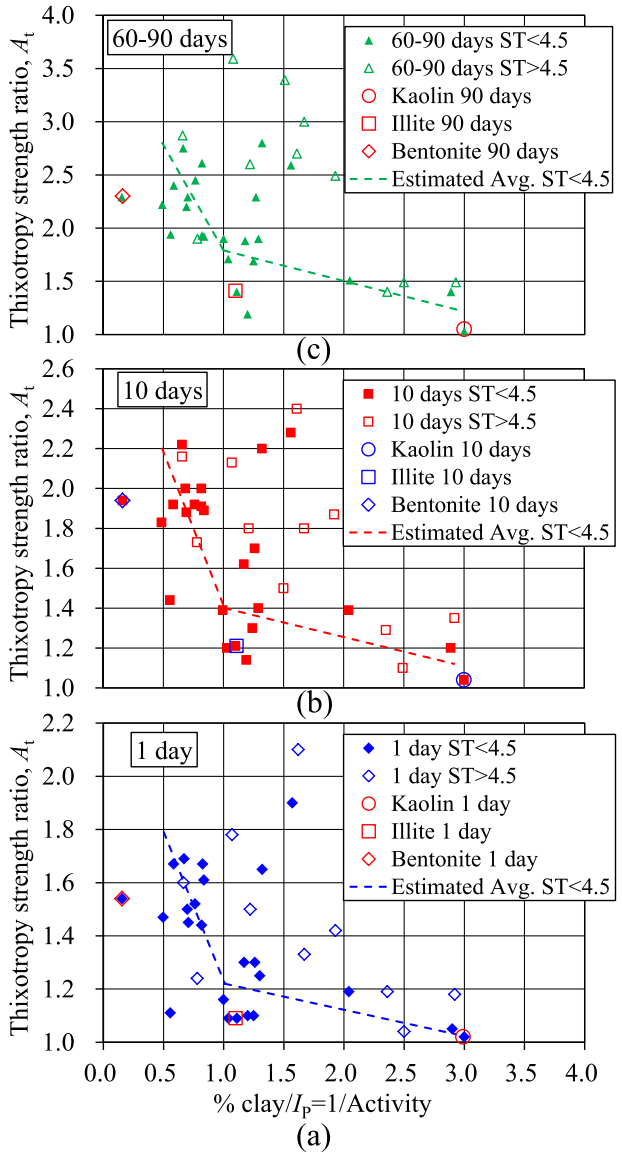

Fig. 7. Thixotropy strength ratio as function of Activity^{-1} = %clay/I_P after 1, 10 and 60–100 days (Lunne and Andersen, 2007).

5. Conclusions and remarks

This paper provides an overview of research on the thixotropy of soil in the past decades. Based on the up-to-date literature review, several conclusions and remarks can be drawn, as follows:

(1) Thixotropy of soil is a process of spontaneous dissipation of externally applied energy by remoulding. Thixotropic behavior is a result of microstructural effect, including particle rearrangement, adsorbed water structure changes and ions redistribution. More advanced analytical techniques methods to investigate the mechanism of thixotropy are recommended. Up to now, there are some thixotropic models developed by researchers. However, more research is still needed to build a well-characterized model and a comprehensive theory of thixotropy in the future.

(2) Fall cone test is a satisfied method to measure the thixotropy strength recovery of soil. Bender element test to measure the shear modulus changes with time is a non-destructive and recommended method to evaluate the thixotropic effect on soil. For engineering application, a widely accepted standard and procedures to measure the thixotropy hardening of soil needs to be established.

(3) In general, thixotropy has the greatest effect on soil strength recovery at water content close to the liquid limit. Nevertheless, there still remain ambiguous findings from the literature. The thixotropic effect is more significant for soils with high activity due to the various crystal structures of different clay minerals. High salt concentration will reduce thixotropic effect of soil by shrinking the thickness of electrical double layer to restrict particle rearrangement. However, in order to use for engineering design and construction, the correlations between thixotropy strength ratio and basic soil properties need to be well established.

For further consideration, the effect of in-situ water content changes due to seepage flow induced by hydraulic gradient during installation of foundations, as well as deep-sea temperature on thixotropy strength recovery should be paid more attention in the future. Besides, how to evaluate and distinguish the strength recovery of soils induced by thixotropy or reconsolidation, as well as their effects on the slope stability and foundation safety, needs more study.

Declaration of Competing Interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, “Thixotropy of soft clay: A review”.

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References

Abdou, M.I., Ahmed, H.E.S., 2013. A study on the thixotropy of Egyptian bentonite suspensions. Pet. Sci. Technol. 31 (19), 1980–1991.
Abu-Farsakh, M., Rosti, F., Souri, A., 2015. Evaluating pile installation and subsequent thixotropic and consolidation effects on setup by numerical simulation for full-scale pile load tests. Can. Geotech. J. 52 (11), 1734–1746.
Al-Janabi, H.A., Aubeny, C.P., 2019, July. Experimental measurement of thixotropy and sensitivity in Gulf of Mexico Clay. In: The 29th International Ocean and Polar Engineering Conference. International Society of Offshore and Polar Engineers.
Aminpour, P., 2019. Multiscale Modeling of Thixotropy in Soft Clays. Drexel University.
Andersen, K.H., Jostad, H.P., 2002, January. Shear strength along outside wall of suction anchors in clay after installation. In: The Twelfth International Offshore and Polar Engineering Conference. International Society of Offshore and Polar Engineers.
Andersen, K.H., Jostad, H.P., 2004, January. Shear strength along inside of suction anchor skirt wall in clay. In: Offshore Technology Conference. Offshore Technology Conference.
Andersen, K.H., Lunne, T., Kvalstad, T.J., Forsberg, C.F., 2008, November. Deep water geotechnical engineering. In: Proc. 24th Nat. Conf. of Mexican Soc. of Soil Mechanics, pp. 1–57.
ASTM, 2014. ASTM D653-14: Standard Terminology Relating to Soil, Rock, and Contained Fluids. ASTM International, West Conshohocken, PA, USA.
Barnes, H.A., 1997. Thixotropy—a review. J. Non-Newtonian Fluid Mech. 70 (1–2), 1–33.
Blake, G.R., Gilman, R.D., 1970. Thixotropic changes with aging of synthetic soil aggregates. Soil Sci. Soc. Am. J. 34 (4), 561–564.
Boswell, P.G.H., 1948. A preliminary examination of the thixotropy of some sedimentary rocks. Q. J. Geol. Soc. 104 (1–4), 499–526.
Burgers, J.M., Blair, G.W.S., 1949. Report on the Principles of Rheological Nomenclature. North-Holland Publishing Company. International Council of Scientific Unions. Joint Committee on Rheology.

Cabrera, J.G., Smalley, I.J., 1973. Quickclays as products of glacial action: a new approach to their nature, geology, distribution and geotechnical properties. Eng. Geol. 7 (2), 115–133.
Chan, C.M., 2015. Strength recovery of remolded dredged marine clay: thixotropic hardening vs. induced cementation. Electron. J. Geotech. Eng. 20, 5847–5858.
Chan, C.M., Yong, H.Y., 2014. Comparing the thixotropic and lightly solidified hardening behavior of a dredged marine clay. Eng. Tech. Appl. Sci. Res. 4 (5), 706–710.
Cronin, S.J., Neall, V.E., Lecointre, J.A., Palmer, A.S., 1999. Dynamic interactions between lahars and stream flow: a case study from Ruapehu volcano, New Zealand. Geol. Soc. Am. Bull. 111 (1), 28–38.
Day, P.R., 1954. Effect of Shear on Water Tension in Saturated Clay (Reports to Western Regional Technical Committee).
Dexter, A.R., Horn, R., Kemper, W.D., 1988. Two mechanisms for age-hardening of soil. J. Soil Sci. 39 (2), 163–175.
Díaz-Rodríguez, J.A., Santamarina, J.C., 1999. Thixotropy: the case of Mexico city soils. In: XI Panamerican Conf. on Soil Mech. and Geotech. Eng, pp. 441–448.
Doglioni, A., Simeone, V., 2013. Recovery of strength along shear surfaces in clay soils. In: Landslide Science and Practice. Springer, Berlin, Heidelberg, pp. 183–188.
Doughty, L.J., Buckley, R.M., Jardine, R.J., 2018. Investigating the effect of ageing on the behaviour of chalk putty. In: Engineering in Chalk. .[Published online ahead of print 16 August 2018.] Available from. https://www.icevirtuallibrary.com/doi/abs/10.1680/eiccf, 64072.
Dullaert, K., Mewis, J., 2006. A structural kinetics model for thixotropy. J. Non-Newtonian Fluid Mech. 139 (1–2), 21–30.
Freundlich, H., 1935. Thixotropy (Vol. 1). Hermann & cie.
Frydman, S., Talesnick, M., Geffen, S., Shvarzman, A., 2007. Landslides and residual strength in marl profiles in Israel. Eng. Geol. 89 (1–2), 36–46.
Gagnoud, M., Lajeunesse, P., Desrosiers, G., Long, B., Stora, G., 2008. Litho-and biofacies analysis of postglacial marine mud using CT-scanning. Eng. Geol. 103 (3), 106–111.
Heymann, L., Noack, E., Kämpfe, L., Beckmann, B., 1996, August. Rheology of printing inks—some new experimental results. In: Ait-Kadi, et al. (Eds.), Proceedings of the XIIth Congress on Rheology. Laval University, Quebec City, Que, pp. 451–452.
Hu, W., Xu, Q., Wang, G., Scaringi, G., Mcsaveney, M., Hicher, P.Y., 2017. Shear resistance variations in experimentally sheared mudstone granules: a possible Shear-Thinning and thixotropic mechanism. Geophys. Res. Lett. 44 (21), 11–040.
Huang, Y., Wang, L., 2016. Laboratory investigation of liquefaction mitigation in silty sand using nanoparticles. Eng. Geol. 204, 23–32.
Jacobsson, A., Pusch, R., 1972. Thixotropic action in remoulded quick clay. Bulletin of the International Association of Engineering Geology-Bulletin de l'Association Internationale de Géologie de l'Ingénieur 5 (1), 105–110.
Jeanjean, P., 2006, January. Setup characteristics of suction anchors for soft Gulf of Mexico clays: experience from field installation and retrieval. In: Offshore Technology Conference. Offshore Technology Conference.
Jeong, S.W., Locat, J., Leroueil, S., 2012. The effects of salinity and shear history on the rheological characteristics of illite-rich and Na-montmorillonite-rich clays. Clay Clay Miner. 60 (2), 108–120.
Jeong, S.W., Locat, J., Torrance, J.K., Leroueil, S., 2015. Thixotropic and anti-thixotropic behaviors of fine-grained soils in various flocculated systems. Eng. Geol. 196, 119–125.
Kamil, A.S., Aljorany, A.N., 2019. Thixotropic hardening of Fao clay. J. Eng. 25 (5), 68–78.
Kerr, P.F., Drew, I.M., 1968. Quick-clay slides in the USA. Eng. Geol. 2 (4), 215–238.
Khaldoun, A., Moller, P., Fall, A., Wegdam, G., De Leeuw, B., Méheust, Y., Bonn, D., 2009. Quick clay and landslides of clayey soils. Phys. Rev. Lett. 103 (18), 188301.
Kul'chitskii, G.B., 1975. Thixotropy of soils of the middle Ob region and its consideration when constructing pile foundations. Soil Mech. Found. Eng. 12 (3), 168–170.
Lu, N.Z., Suhayda, J.N., Prior, D.B., Bornhold, B.D., Keller, G.H., Wiseman, W.J., Wright, L.D., Yang, Z.S., 1991. Sediment thixotropy and submarine mass movement, Huanghe Delta, China. Geo-Mar. Lett. 11 (1), 9–15.
Lunne, T., Andersen, K.H., 2007, January. Soft clay shear strength parameters for deepwater geotechnical design. In: Offshore Site Investigation and Geotechnics, Confronting New Challenges and Sharing Knowledge. Society of Underwater Technology.
Mainsant, G., Chambon, G., Jongmans, D., Larose, E., Baillet, L., 2015. Shear-wave-velocity drop prior to clayey mass movement in laboratory flume experiments. Eng. Geol. 192, 26–32.
Mitchell, J.K., 1961. Fundamental aspects of thixotropy in soils. Trans. Am. Soc. Civ. Eng. 126 (1), 1586–1620.
Moretto, O., 1948. Effect of natural hardening on the unconfined compression strength of remoulded clays. In: Proceedings of the 2nd International Conference on Soil Mechanics and Foundation Engineering, Rotterdam, the Netherlands, Vol. 1, pp. 137–144.
Olphen, H.V., 1977. An Introduction to Clay Colloid Chemistry, for Clay Technologists, Geologists, and Soil Scientists (No. 2nd edition).
Osipov, V.I., Nikolaeva, S.K., Sokolov, V.N., 1984. Microstructural changes associated with thixotropic phenomena in clay soils. Geotechnique 34 (3), 293–303.
Pardo, G.S., Sarmah, A.K., Orense, R.P., 2019. Mechanism of improvement of biochar on shear strength and liquefaction resistance of sand. Geotechnique 69 (6), 471–480.
Park, D., Kutter, B.L., DeJong, J.T., 2014. Effects of thixotropy and cement content on the sensitivity of soft remolded clay. J. Geotech. Geoenviron. 141 (2) (p. 04014095).
Perret, D., Locat, J., Martignoni, P., 1996. Thixotropic behavior during shear of a fine-grained mud from Eastern Canada. Eng. Geol. 43 (1), 31–44.
Peterfi, T., 1927. Arch. Entwicklungsmech. Organ 112, 660–695.
Rinaldi, V.A., Clariá Jr., J.J., 2016. Time dependent stress–strain behavior of bentonite slurries; effect of thixotropy. Powder Technol. 291, 311–321.
Romanov, S.V., Romanov, D.A., 1997. Procedure for impressing reinforced-concrete piles into leader holes using soil thixotropy. Soil Mech. Found. Eng. 34 (1), 22–24.
Seed, H.B., Mitchell, J.K., Chan, C.K., 1961. The Strength of Compacted Cohesive Soils, pp. 877–964.
Seng, S., Tanaka, H., 2012. Properties of very soft clays: a study of thixotropic hardening and behavior under low consolidation pressure. Soils Found. 52 (2), 335–345.
Shahriar, A.R., Abedin, M.Z., Jadid, R., 2018. Thixotropic aging and its effect on 1-D compression behavior of soft reconstituted clays. Appl. Clay Sci. 153, 217–227.
Skempton, A.W., Northey, R.D., 1952. The sensitivity of clays. Geotechnique 3 (1), 30–53.
Solonenko, V.P., 1977. Landslides and collapses in seismic zones and their prediction. Bull. Int. Assoc. Eng. Geol. 15 (1), 4–8.
de Souza Mendes, P.R., 2009. Modeling the thixotropic behavior of structured fluids. J. Non-Newtonian Fluid Mech. 164 (1–3), 66–75.
Stempkowska, A., Mastalska-Popławska, J., Izak, P., Ogłaza, L., Turkowska, M., 2017. Stabilization of kaolin clay slurry with sodium silicate of different silicate moduli. Appl. Clay Sci. 146, 147–151.
Sun, H., Masin, D., Najser, J., Nedela, V., Navratilova, E., 2019. Bentonite microstructure and saturation evolution in wetting-drying cycles evaluated using ESEM, MIP and WRC measurements. Géotechnique 69 (8), 713–726.
Sun, X., Li, X., Zheng, B., He, J., Mao, T., 2020. Study on the progressive fracturing in soil and rock mixture under uniaxial compression conditions by CT scanning. Eng. Geol. 279.
Suthaker, N.N., Scott, J.D., 1997. Thixotropic strength measurement of oil sand fine tailings. Can. Geotech. J. 34 (6), 974–984.
Utomo, W.H., Dexter, A.R., 1981. Age hardening of agricultural top soils. J. Soil Sci. 32 (3), 335–350.
Det Norske Veritas, 2005. Geotechnical design and installation of suction anchors in clay. In: DNV Recommended Practice RP-E303.
Yalcin, A.S., McIntosh, R., 1961. Some rheological parameters of clays and their thixotropic behavior. Can. J. Chem. Eng. 39 (2), 76–80.
Yang, S., Andersen, K.H., 2016. Thixotropy of marine clays. Geotech. Test. J. 39 (2), 331–339.
Yap, J., Leong, Y.K., Liu, J., 2011. Structural recovery behavior of barite-loaded bentonite drilling muds. J. Pet. Sci. Eng. 78 (2), 552–558.
Yenes, M., Monterrubio, S., Nespereira, J., Casas, D., 2020. Apparent overconsolidation and its implications for submarine landslides. Eng. Geol. 264, 105375.
Yoon, J., El Mohtar, C.S., 2014. Rheological properties of sodium pyrophosphate modified bentonite suspensions for seepage control. Eng. Geol. 179, 32–40.
Zakeri, A., Liedtke, E., Clukey, E.C., Jeanjean, P., 2014. Long-term axial capacity of Deepwater jetted piles. Geotechnique 64 (12), 966–980.
Zhang, G., Yin, H., Degroot, D.J., 2013. Thixotropism of micron-sized saltwater clay flocs. Géotech. Lett. 3 (4), 162–165.
Zhang, X.W., Kong, L.W., Yang, A.W., Sayem, H.M., 2017. Thixotropic mechanism of clay: a microstructural investigation. Soils Found. 57 (1), 23–35.